2 Direct Observations

The current LIGO instruments are the culmination of more than four decades of work. During its first few months of operation, from late summer through early winter, 2015, all the effort paid off. LIGO detected three candidate gravitational wave sources, the first-ever direct detections of gravitational waves. The first event, in September (GW150914), occurred within a week of turning the experiment on and before the observatories had even begun official scientific operations. The other two events were in October (LVT151012) and December (GW151226), respectively. Careful analysis indicated that two of the events were binary mergers. The October event fell short of the statistical significance required to declare it a true source, though it is possibly a merger event like the other detections. These are the three strongest events found during the first three months of Advanced LIGO operations. Figure 2.1 shows the evolution of the waveforms over time. The two confirmed sources are described briefly in the sections below.

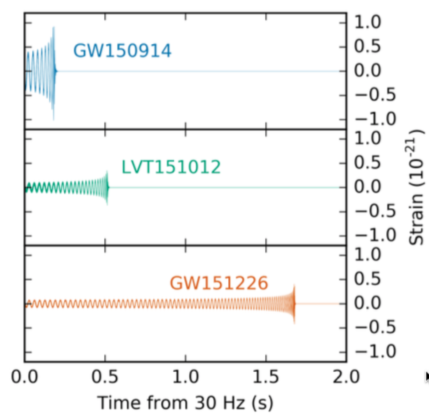

Figure 2.1: Shown here are plots of the gravitational wave waveforms from LIGO for the two black hole merger events, GW150914 and GW151226, respectively, plus the merger candidate LVT151012. The strain is plotted on the vertical axis, and the time since entering the detectors' sensitivity band (at 30 Hz). From LSCollaboration (2016).

2.1 GW150914

The event, called GW150914 to reflect the UT (basically, Greenwich Mean Time, the time in London, England, but with no changes for daylight savings) date of its detection, is thought to be the result of the merger of two stellar-mass black holes. The detection was the result of correlating the signals from the two LIGO observatories, one at Hanford, Washington and the other at Livingston, Louisiana. The correlations involved searches for excess signal in each detector within a 15 ms window corresponding to the light travel time between the Livingston and Hanford sites. Matching candidates were then compared to templates created using computational models for binary merger systems. Both of these methods will be discussed in more detail in Section 5.

In a binary merger, the orbital frequency increases as the two objects, either black holes or neutron stars, spiral toward one another, losing energy each orbit to gravitational waves. At first this change is quite slow, with the orbital radius changing only slightly with each orbit. However, as the separation[1] between the objects approaches the Schwarzschild radius (R_{Sch}) of the system components, the radial evolution increases. Finally, at the last stable orbit, at three times R_{Sch} for non-spinning black holes, the components plunge inward, merging into a single object. In principle, the original components can be some combination of black holes and neutron stars, but the final object is nearly always a Kerr (spinning) black hole.

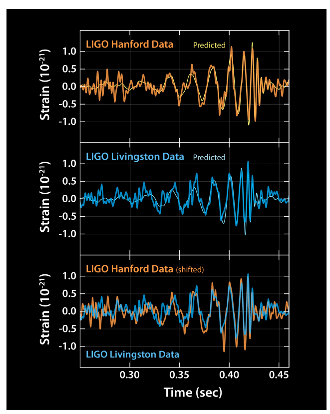

Figure 2.2: The signals from Hanford (top, orange) and Livingston (middle, blue) for GW150914. The bottom panel shows the two superimposed, with the Hanford data shifted approximately 7 ms to account for the light travel time between the two sites. The top two panels show a computed template superimposed over the measured waveforms. Credit: Caltech/MIT/LIGO Lab

This orbital evolution is imprinted on the gravitational waveforms shown in Figure 2.2. Both the Hanford (top) and Livingston (middle) panels in the figure show the frequency of the waves increasing as their amplitude increases. At the point of the black hole merger,

[1] "Separation" is not a very good term to describe such a distorted spacetime, but it does partially convey what is happeining.

the amplitude decays exponentially to zero. Notice that the amplitude in these plots is measured in terms of *strain*, which is defined to be the change in length over length. Mathematically, the strain, h, is defined as follows.

$$h \equiv \frac{\Delta L}{L_0} \tag{2.1}$$

In this expression, L_0 is the length of an object when gravitational waves are not present (it is the unperturbed distance between the LIGO test masses in this case, as described in Section 3) and ΔL is the change in that distance caused by a passing gravitational wave.

The characteristic evolution of the gravitational wave frequencies is described as a "chirp." It starts out slow and then increases rapidly as the merger happens. Since the frequency is basically twice the orbital frequency of the system, this evolution is easy to understand: smaller orbital radii correspond to higher orbital frequencies. The frequency evolution for GW150914 is shown in Figure 2.3, with the signal from Hanford in the left panel and Livingston on the right. The Figure shows that the detectable frequency starts off around 35 Hz and sweeps upward to 250 Hz before the black holes merge.

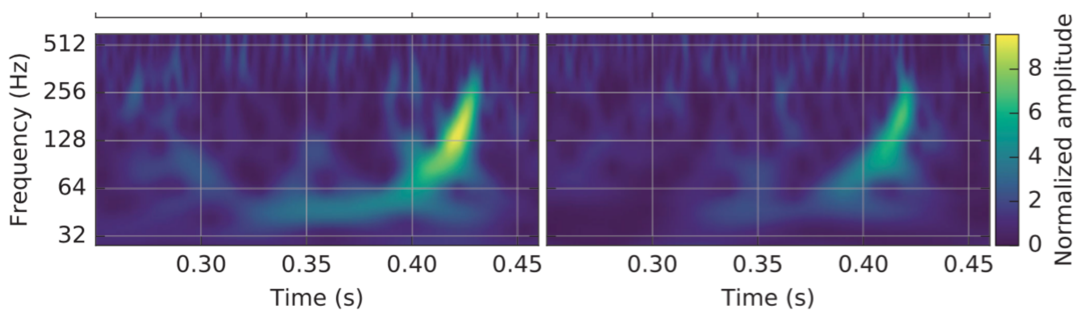

Figure 2.3: Frequency evolution of GW150914 gravitational wave signals from the Hanford (left) and Livingston (right) observatories. The frequency starts at around 32 Hz and sweeps upward to 250 Hz before the black holes merge. From Abbott & et al. (2016b).

Assuming that general relativity is the correct description of the event, the particulars of the merger can tell us what sort of system produced the gravitational waves. For instance, if the total mass is many times the mass of the Sun, then we know that at least one of the objects is a black hole. The maximum mass for two neutron stars is not likely to be above $3\,M_\odot$ to $5\,M_\odot$, where $M_\odot$ is the Sun's mass. In theory, the mass could be larger, but nearly all the measured neutron star masses to date are consistent with the maximum white dwarf mass limit of $1.4\,M_\odot$[2].

[2]This limit is called the Chandrasekhar mass, after the scientist who first discovered it.

The orbital period also helps constrain the type of system. If the merger happens at a relatively low frequency, then we know that one of the objects is a massive black hole. The Schwarzschild radius for a massive black hole is large, which corresponds to a lower orbital frequency at the point of merging. On the other hand, if the merger occurs at a high orbital frequency, then the objects were able to get relatively close before merging. In that case, both objects have smaller radii. They could both be relatively small black holes, or they could be neutron stars, or a combination of the two. For reference, the Schwarzschild radius of a solar mass black hole is 3 km, and R_{Sch} is proportional to mass, as shown in Equation 2.2.

$$R_{Sch} = \frac{2GM}{c^2} \tag{2.2}$$

In the case of GW150914, the frequency at the merger indicated that the objects approached fairly close before the merger.

The frequency and its evolution also provide the total mass of the system. For this system, the best fit of the general relativistic waveform to data occurs for objects of 36 $M_\odot$ and 29 $M_\odot$ merging to form an object with a final mass of 62 $M_\odot$: all these masses indicate that the system began as two black holes orbiting each other, and that it evolved to a single spinning black hole. Note the mass difference between the initial and final states. This was the energy lost to gravitational waves: three solar masses ($3\,\mathrm{M}_\odot$).

These mass values were determined by correlating the signals from each observatory with over 250,000 computed templates of black hole merger systems calibrated to supercomputer computations. The grid of templates covered systems with total masses up to 100 $M_\odot$, taking steps of 1 $M_\odot$ between grid points. The black hole spins ranged up to near-maximally spinning models. See Abbott & et al. (2016b) and its references for details.

To get an idea of how the mass of the initial black holes will affect the gravitational wave signal, you can use the simulations at the Gravitational Wave Optics website. They have created some instructive simulations addressing different aspects of LIGO and its science, and we will be using several of them in this course. The one you should look at now is called Inspiral Signal. All of these applets are written in Java. If you have trouble with them, see the help documents on running Java linked on the course website.

The detection of GW150914 is remarkable for a number of reasons. First, because it was the first direct detection of gravitational waves ever, as we have already mentioned. Beyond that, the source of waves was surprising, though perhaps not in retrospect. The sources that most scientists expected to see first consist of two merging neutron stars, or perhaps a neutron star - black hole merger system. There is already strong evidence for the existence of these kinds of systems. For example, double neutron star systems are already known, and some, like PSR 1913+16 (Taylor & Weisberg, 1982), are known to be losing orbital energy, presumably via emission of gravitational waves. Additionally, black hole - neutron star systems are thought to be among the progenitors of short gamma-ray burst events. Finding examples of these in the LIGO data would have surprised no one.

Instead, a black hole - black hole merger was seen. Few scientists really expected that. It is not that such systems would not emit copious gravitational radiation. They would. But astronomers had no idea what the number of such systems might be. Black holes are difficult to see. A merging black hole system like the one in GW150914 is essentially invisible in any type of radiation other than gravitational waves. There could be millions of them in the Galaxy, there could be none. Before this result, nobody knew.

Another reason that the detection of GW150914 was remarkable is that this was the first ever *direct detection of black holes*. Evidence for the existence of black holes has been mounting over the past three decades or so, becoming stronger and stronger to the point where nobody seriously doubted their existence by the time LIGO began operating. However, all the evidence prior to this event had been indirect, just as the evidence for gravitational waves before this, while completely convincing, was indirect. This observation, thus, provides a *direct* detection of not only the spacetime ripples from this merger system, but of the black hole components of the system.

2.2 GW151226

On the day after Christmas, December 26, 2015, at 03:38:53 UT, LIGO discovered its second merger event. There was a delay of 1.1 ms between the Hanford detection and the Livingston detection, with Hanford being first. December 26 is traditionally called Boxing Day in Britain and many of its former colonies, and so this event is sometimes referred to as the Boxing Day event.

GW151226 was not as strong as the September event, despite the comparable distances of the two objects from Earth. This was because the GW151226 system was less massive, and so the total energy it radiated was less and the amplitude of the waves was lower than was the case in the more massive system. However, because the merging black holes were smaller - recall that the Schwarzschild radius scales linearly with mass - the black holes were able to spiral closer together before merging. This system, therefore, spun up to higher frequencies before the black holes coalesced.

Detailed analysis of the waveform for GW151226 indicates that the system initially contained $21.8\,\mathrm{M}_\odot$ of mass. Initially, there was a $14.2\,\mathrm{M}_\odot$ object and a $7.5\,\mathrm{M}_\odot$ object. They merged to form a $20.8\,\mathrm{M}_\odot$ object. Since all of these masses are well above the mass limit for a neutron star ($\sim 3\,\mathrm{M}_\odot$), they are assumed to be black holes. The uncertainties on the masses of these objects is much higher than in the case of GW150914 because of the lower signal-to-noise in this detection. The best fit values indicate that the system radiated away $1\,\mathrm{M}_\odot$ of energy in gravitational waves, and that the final black hole has an angular momentum 70% of the maximum possible for such an object.

Figure 2.4 shows the waveform and chirp plots for the event. The GW151226 event is much harder to pick out than the September event. Notice that, while the GW151226 event had an initial frequency comparable to that of GW150914, the chirp signal increased to a much higher level, around 450 Hz, before coalescence of the black holes. This is an indication that the December detection resulted from a lower-mass system than the September event. Unfortunately, the lower signal-to-noise of the Boxing Day event makes the frequency evolution hard to discern by eye in the plotted data.

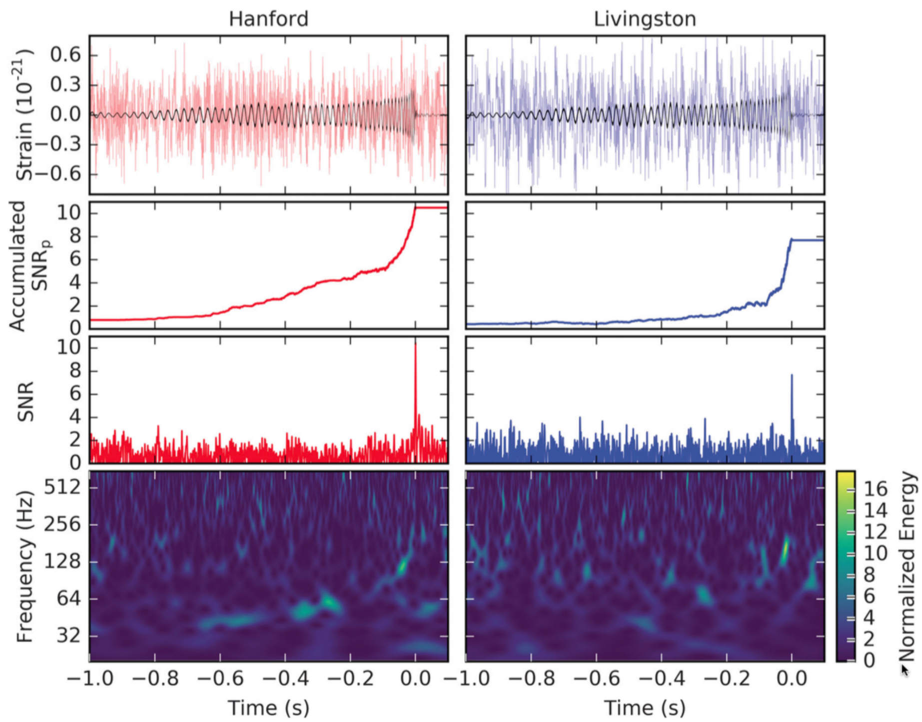

Figure 2.4: This figure shows the evolution of the waveform during the merger of the GW151226 system (top), and the characteristic "chirp" of the frequency evolution (bottom). The black curves are the reconstructed best-fit model waveforms. In between are plots of the signal to noise ratio of the event. While this event is not as obvious to the eye as the GW150914 event, it is still quite statistically significant. The lower signal is due to the fact that the merging black holes in GW151226 were much less massive than in GW150914. From Abbott & et al. (2016a).

2.3 Implications of These Detections

Both of these events were the first direct detections of gravitational waves, and their importance for our understanding of gravity cannot be overstated in that regard: They provided confirmation of the last long-standing prediction of general relativity. Einstein himself predicted the existence of gravitational waves in 1918, the year after announcing his General

Theory of Relativity, still our best understanding of the nature of gravity. But beyond that, they allowed us, for the first time, to directly observe black holes merging. And that brings us to what might be the most remarkable, and most profound, aspect of this detection.

LIGO has seen an astrophysical phenomenon that would otherwise be undetectable. In that respect, it is just like all the other telescopes that have opened new windows on the universe. Every one of these new telescopes has shown us new types of objects and phenomena that could not be seen by other instruments and that in some cases had not even been imagined by scientists. Where LIGO differs strongly from previous cases, though, is that it is not merely revealing a new part of the electromagnetic spectrum[3]. LIGO does not see another version of the many kinds of "light." LIGO sees the universe in an entirely new way. It senses the ripples in the fabric of spacetime that are caused when a large mass distribution changes rapidly, thus changing the distortions of the spacetime curvature in its immediate vicinity and sending those distortions out into the cosmos.

To emphasize this difference, many of the scientists working on LIGO use the analogy of sound. They often say that LIGO "listens" to the cosmos, as opposed to "looking" at it. This is a useful analogy, especially since the frequency of the waves to which LIGO is sensitive corresponds closely to the range of sound frequencies that humans can hear. In addition, the data, like sound, are a single time-series rather than a many-pixel image. But the analogy must be used with caution. LIGO does not hear sound. Gravitational waves are not sound. They do not even resemble sound waves, not in any way. First of all, sound requires a medium through which to travel; it is a traveling pattern of high and low density distortions in some medium, whether gas, liquid or solid. Space is empty; it provides no such medium. Furthermore, sound is typically a longitudinal wave, with the high and low pressure displacements happening along the direction parallel to the travel of the wave. Gravitational wave distortions, like electromagnetic waves and, to some degree, water surface waves[4], occur in the directions perpendicular to the direction of the waves' travel. What's more, gravitational waves travel at the speed of light, just as electromagnetic waves do. Sound waves do not[5].

So once again, *Gravitational waves are not sound.* Instead, they are the distortions of spacetime itself, and it is these distortions to which LIGO is sensitive. Whether it "hears" them or "sees" them is a matter of taste.[6]

[3]The spectrum includes radio, microwave, infrared, visible, ultraviolet, x-rays and gamma-rays, all essentially forms of light, each with a different frequency (or energy or wavelength).

[4]Note that these are called *gravity waves* in contrast to the *gravitational waves* detected by LIGO.

[5]Though in certain relativistic fluids in which the thermal speeds of the particles approach the speed of light, the sound speed does as well

[6] I suppose we could, if we liked, say that LIGO "tastes" gravitational waves, but that would clearly stretch the analogy with our senses a bit too far.

2.4 Additional Resources

An interesting website with LIGO related subject is Sounds of Spacetime. On this site you will find video and sound files for the 2015 events. Probably best enjoyed using a nice set of headphones. This site is described in more detail on the course Moodle.

In addition, you can look at the Science Summary pages on the LIGO website. There are individual pages for the GW150914 and GW151226 events, as well as an overall detection page.